Task 1.2

Title
Reservoir stimulation and engineering

Projects (presented on the following pages)

Scaling spatial distribution of fractures using borehole images: An application to Basel geothermal reservoir
M. J. Afshari, B. Valley, K. Evans

Simultaneous Visualization of Fluid Flow and Mineral Precipitation in Fractured Porous Media
M. Ahkami, X. Kong, M. O. Saar

Acoustic monitoring of laboratory hydraulic fracture growth under stress and pore pressure
T. E. Blum, B. Lecampion

Cross-borehole characterization of permeability enhancement & heat transport in stimulated fractured media: preliminary results from the ISC experiment at the Grimsel Test Site
Alternative: Work Package 5
B. Brixel, M. Klepikova, M. Jalali, F. Amman, S. Loew

Effect of fluid viscosity on fault frictional behavior
C. Cornelio, E. Spagnuolo, G. Di Toro, M. Violay

Injection Protocol and First Results of Hydraulic Fracturing Experiments at the Grimsel Test Site
Alternative: Work Package 5
N. Dutler, B. Valley, L. Villiger, H. Krietsch, M. Jalali, V. Gischig, J. Doetsch, F. Amann

Impact of CO₂ injection on the hydro-mechanical behaviour of a clay-rich caprock
V. Favero, L. Laloui

Visualizing salt tracers using GPR
P. Giertzuch, J. Doetsch, A. Shakas, M. Jalali, A. Kittilä, H. Maurer

A comparison of the seismo-hydro-mechanical observations during two hydraulic stimulations at the Grimsel Test Site
Alternative: Work Package 5
V. Gischig, J. Doetsch, M. Jalali, F. Amann, H. Krietsch, L. Villiger, N. Dutler, B. Valley

Permeability Changes Induced by Hydraulic Stimulation at the Grimsel Test Site
Alternative: Work Package 5
M. Jalali, V. Gischig, J. Doetsch, H. Krietsch, L. Villiger, N. Dutler, B. Valley, K. F. Evans, F. Amann

A matlab package for thermo-hydraulic modeling and fracture stability analysis in fractured reservoirs
G. Jansen, B. Valley, S. A. Miller

A multi-parametric evaluation of the Wallace-Bott hypothesis in the presence of a fluid source
M. Kakurina, Y. Guglielmi, C. Nussbaum, B. Valley
Tracer based characterization of the connected fracture volume in the DUG Lab at the Grimsel Test Site
*Alternative: Work Package 5*

A. Kittilä, K. Evans, M. Jalali, M. Willmann, M. O. Saar

In situ characterization of groundwater flow and heat transport in stimulated fractured network using DTS

M. Klepikova, B. Brixel, M. Jalali, S. Loew, F. Amann

How much can we interpret mineral surface area with distributions of minerals and pores?

X. Kong, J. Ma, D. Webster, M. O. Saar

Geological characterization and in-situ stress state of the ISC experimental volume

*Alternative: Work Package 5*

H. Krietsch, V. Gischig, F. Amann, J. Doetsch, M. Jalali, B. Valley

Deformation and tilt measurements during the ISC experiment at the Grimsel Test Site

*Alternative: Work Package 5*

H. Krietsch, V. Gischig, B. Valley, F. Amann

Core-scale reactive transport modelling of injection of CO₂-charged brine into natural sandstone

J. Ma, X. Kong, M. O. Saar

Mixed finite element method for recovering stress and displacement fields

M. Nejati, T. Driesner

Numerical Modeling of Natural Convection in Fractured Media

J. Patterson, T. Driesner

Enhancing drilling performance by combining conventional and thermal spallation drilling: A feasibility study

E. Rossi, M. A. Kant, C. Madonna, M. O. Saar, P. R. von Rohr

Pico-seismicity during hydraulic stimulation experiments at the Grimsel Test Site

*Alternative: Work Package 5*

L. Villiger, V. Gischig, J. Doetsch, H. Krietsch, M. Jalali, N. Dutler, B. Valley, K. Evans, F. Amann, S. Wiemer

An Implicit Level Set Scheme to simulate planar 3D hydraulic fracture propagation

H. Zia, B. Lecampion
Scaling spatial distribution of fractures using borehole images: An application to Basel geothermal reservoir

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Motivation
Characterization of the natural fractures is key to create a geological model which permits the accurate design and assessment of Enhanced Geothermal System (EGS) development strategies. Our knowledge about the existing fractures in early stages of reservoir creation is restricted to borehole data. Constraining the stochastic fracture network realizations, also referred as Discrete Fracture Networks (DFN), is expected to improve our predictions of seismo-hydromechanical response of a reservoir during hydraulic stimulation. The primary motivation of this research is to constrain three dimensional (3-D) spatial distribution of fractures in a reservoir using borehole observations. First of all, we start with scaling of fracture patterns in a deep borehole such as Basel-1. We base our analysis on the fractures inferred from acoustic televiewer logs in Basel-1 by Ziegler et al. (2015). Then, we use synthetic fracture networks to explore the possible extraction of scaling relationships of 2-D and 3-D spatial organizations from 1-D data.

Methodology
1. Characterization of borehole data: The scaling exponent of fracture patterns (in any dimension) can be computed by fitting a power-law to the corresponding correlation function such as equation 1 where,

\[ C(r) = \frac{1}{N_p} N_\rho(r) \sim r^D \]  

\[ r \] is the distance between two fractures.

\[ N \] the total number of fractures and

\[ N_p \] is the number of pairs less than \( r \) apart, 

\[ D \] is the scaling exponent of the complete fracture dataset and the spatial distribution of fractures in a reservoir using borehole images.

2. Generate synthetic networks: According to the literature, the only DFN model with established stereological relationships (i.e. relations among the spatial distributions in one, two and three dimensions) is a dual-power law (Davy et al., 1990; Darcel et al., 2003). This research is focused on performing a critical analysis of such stereological relationships in one and two dimensions, and its possible extension to three dimensions. Equation 2 represents DFN model we apply where,

\[ n(l, l+dl) \sim l^{a-1} \]  

\[ n(l, l+dl) \] is the number of fractures in the length range of \( l, l+dl \), 

\[ l \] is the domain length, 

\[ D \] is the correlation dimension, 

\[ a \] is the length exponent with \( c \) as a constant.

3. Analyze the possible application of stereological relationships to Constrain DFNs: The process of such an analysis is given in the following flowchart.

• There is a large discrepancy between the analytical predictions and stereological analysis in synthetic networks. 
• The stereological analysis we performed shows that \( D_2D \) cannot be reliably estimated from 1-D data. 
• Estimating 3-D spatial distribution form one boreholes involves a huge uncertainty associated with estimating \( D_2D \). In addition, there is no information about the length distributions of 3-D fracture planes in the reservoir.

Acknowledgements
The research leading to these results has received funding from the European Community’s Seventh Framework Program under grant agreement No. 608553 (Project IMAGE).

References


Simultaneous Visualization of Fluid Flow and Mineral Precipitation in Fractured Porous Media

Mehrdad Ahkami*, Xiang-Zhao Kong, Martin O. Saar
Geothermal Energy and Geofluids, Institute of Geophysics, ETH Zurich, Switzerland
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Background - Motivation
Mineral precipitation during Enhanced Geothermal Systems (EGS) can reduce the efficiency and life time.

Major causes of mineral precipitation:
• Perturbation of temperature and pressure
• Mixing of two different fluids
• Introducing of a fluid that is out of equilibrium with mineral phase

Visualization of Flow by Particle Shadow Velocimetry (PSV)
Fluid is seeded with tracer particles, which are assumed to follow flow dynamics. The motion of seeding particles is illuminated and recorded to determine flow velocity.

Lattice Boltzmann simulations, using lbHydra
• Lattice Boltzmann method (LBM) was used to calculate the permeability and pressure drop in media to be used in experimental design.
• LBM method was used to design the cell for PSV experiment, to ensure one order of magnitude difference in velocity between fracture and matrix.

Acknowledgement
The project is funded by ETH Research Grant under grant No. ETH-12 15-2.

References:
I. Introduction

- Fluid-driven fracturing present in a wide range of applications:
  - Oil and gas extraction
  - Geothermal energy recovery
  - CO2 sequestration
- Need for models to:
  - Efficiently fracture the targeted rock formation and quantify fracturing
  - Better understand the physics of fluid-driven fracturing
  - Get an estimate of fracture size and shape during growth
- Theoretical models:
  - Analytical or numerical solution
  - Based on assumptions on fluid and rock properties, geometry...
- Scaled laboratory experiments:
  - Allow to validate theoretical predictions
  - Provide complete datasets of individual experiments performed under controlled conditions
  - Include physical limitations
- History of lab-scale geophysics for geomechanical problems (Hall, 2009)

II. Existing work

- The DelFrac Consortium at TU Delft pioneered this field by building an acoustic monitoring setup inside a triaxial press applying three independent stresses on a cubic specimen (Groenenboom, 1998).
- The CSIRO group in Melbourne also has a triaxial press used for hydraulic fracturing experiments, but mostly uses photometric monitoring methods (Kovalyshen et al., 2014).

Comparison of existing setups and planned GEL setup

<table>
<thead>
<tr>
<th>TU Delft</th>
<th>CSIRO</th>
<th>GEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen size</td>
<td>300 mm cube</td>
<td>300 mm cube</td>
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<tr>
<td>Max. stress</td>
<td>30 MPa</td>
<td>25 MPa</td>
</tr>
<tr>
<td>Max. injection pressure</td>
<td>50 MPa</td>
<td>75 MPa</td>
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<tr>
<td>Transducers</td>
<td>48</td>
<td>6</td>
</tr>
<tr>
<td>Frequency</td>
<td>0.5 MHz</td>
<td>1 MHz</td>
</tr>
</tbody>
</table>

- Limitations:
  - Maximum applicable stress
  - Injection rate: controls experiment duration
  - Measurement of pore pressure not possible in most setups

III. Laboratory setup

- Planned experimental setup:
  - Triaxial frame with cubic-shaped specimens of up to 250 mm in length
  - Independent stresses on each axis up to 20 MPa
  - High-pressure injection pump with a maximum pressure of 50 MPa
  - Flow rate ranging from 1 μL/min to 90 mL/min
  - Glued wellbore and notching at the bottom for fracture initiation
- Triaxial cell in testing phase, loaded horizontally

References


IV. Acoustic monitoring

- Acoustic monitoring setup:
  - 54 longitudinal and 10 shear piezoelectric transducers
  - 32 sources swept through a multiplexer
  - Function generator and high-power amplifier to create 300 Vp excitation signal
  - 32 receivers connected to high-speed board for simultaneous acquisition at 50 MHz
  - Transducers on all sides, most transducers on the sides parallel to the fracture plane
- Full acquisition duration on the order of a few seconds
- Schematic of the triaxial cell with confining stresses, injection line and piezoelectric transducers, simplified propagation modes at bottom right

Wave modes propagating through the sample:

- $T$: transmitted waves go through the fluid-filled fracture and carry information on the fracture thickness
- $R$: waves that are reflected at the fracture interface carry information about the position of the fracture, and also about the occurrence of fluid lag
- $D$: waves diffracted from the tip of the fracture carry information about the position of the fracture tip (Groenenboom et al., 2001)

V. Preliminary results

- Thickness estimation (Groenenboom and Fokkema, 1998; Kovalyshen et al., 2014)
  
  \[
  T(\omega, \beta) = \frac{(1-r^2)e^{-\beta h}}{1-r^2 e^{-2\beta h}} \tag{1}
  \]
  
  - $h$: fluid thickness
  - $\omega$: frequency
  - $r$: $\rho_s/\rho_f$ densities of solid and fracturing fluid
  - $\alpha$: $v_s/v_f$ P-wave velocities of solid and fracturing fluid
  - Impedance ratio $Z = \frac{\rho_s c_s}{\rho_f c_f}$

- Thickness changes:
  - Delayed arrival when fluid thickness increases due to travel through fluid layer
  - But also decreased amplitude: change in transmission coefficient

VI. Future applications

- Investigation of the process zone in quasi-brittle materials
- Fracture propagation in anisotropic or inhomogeneous materials
- Effects of mixed-mode fracturing with fracture reorientation
- Fracture profile for different fluid types: Newtonian, “power-law” …

VII. Conclusion

- Unique experimental capabilities with triaxial stresses and pore pressure
- Dense ultrasonic monitoring for improved fracture geometry estimation
- Growing list of applications
- Full operation expected end of 2017!
Cross-borehole characterization of permeability enhancement & heat transport in stimulated fractured media: preliminary results from the ISC experiment at the Grimsel Test Site

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Motivation
1. Detect and characterize permeability enhancement in response to hydro-shearing
2. Understand the effects of stimulation on fluid flow and heat transport
3. Identify the permeable fractures that contribute to heat transport

Approach & Concepts

Methods

Preliminary field results

Permeability enhancement

Heat transport

Conclusions
1. Pressure transients from hydraulic tests completed following the same procedure, both before and after hydraulic shearing, show that the connectivity of the fracture network increased, at least over a scale of 10 m.
2. Both NEW and ENHANCED connections have been detected through hydraulic testing (see Fig. 5).
3. The propagation of heat during thermal tracer tests is constrained to discrete flow pathways (see Fig. 6), which helps us identifying the permeable fractures that contributing to heat transport.
Effect of fluid viscosity on fault frictional behavior

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Introduction

Tectonic faults are often lubricated by viscous fluid which can have different nature e.g. gas, water, brine, melt and viscosities varying over 7 order of magnitude (from $10^{-4}$ for water to $10^{3}$ Pa·s$^{-1}$ for melt at high temperature). Moreover, understanding fluids viscosity effects on fault dynamics can shed light on the induced seismicity in engineering reservoirs where fluids with viscosity ranking from $1$ mPa·s$^{-1}$ to $1000$ mPa·s$^{-1}$ are also injected during hydraulic fracturing process in order to increase the permeability. Here, we examine the mechanisms coming into play in presence of viscous lubricant film between the rock slip surfaces during both earthquake nucleation (slip rate from $\mu$m·s$^{-1}$ to mm·s$^{-1}$) and propagation (mm·s$^{-1}$ to m·s$^{-1}$) where mixed lubrication and fully lubricated regime might be activated, using rotary shear tests on precut samples of Westerly granite.

SHIVA Set-Up

![SHIVA Set-Up](image)

**Figure 1:** Slow to High Velocity Apparatus. (a) 1. Large electric motor. 2. Bellow couplings. 3. Sprag clutch. 4. Gear box. 5. Air actuator. 6. Steel arm to amplify the axial load. The axial load is imposed by the air actuator and monitored by a computer. The torque is measured using a torque bar.

Table of Experiments

<table>
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<th>V [mm/s]</th>
<th>H$_2$O</th>
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<td>s1303</td>
<td>s1316</td>
<td>s1305</td>
<td>s1389</td>
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</tbody>
</table>

Results

![Results](image)

**Figure 2:** Static and Peak friction coefficient vs Sommerfield number

**Figure 3:** Dynamic friction coefficient and Frictional energy vs Sommerfield number

Conclusion

- 30 tests in rotary shear apparatus have been performed, using different viscous fluid and imposing different target slip rate
- Three different lubricated regime have been detected
- Static friction coefficient is strongly dependent on fluid viscosity
- Dynamic friction coefficient is strongly dependent on fluid rheology and viscosity
- Frictional energy does not depend on the nature of the fluid, but it depends on fluid viscosity and velocity
- It increases in boundary and mixed regimes
- It abruptly decreases in fully lubricated regime
- Lubrication $\neq$ Easy EQ Propagation

References

Injection Protocol and First Results of Hydraulic Fracturing Experiments at the Grimsel Test Site

Nathan Dutler*, Benoît Valley*, Linus Villiger**, Mohammedreza Jalali***, Valentin Gischig***, Joseph Doetsch*** & Florian Amann***

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Injection protocol

- Injection of ~1 m³ fluid for each injection phase
- The injection protocol includes the following elements:
  1. Initial pulse tested to verify packed interval integrity
  2. A formation breakdown test at relatively low flow rate (i.e. 5 lpm)
  3. A main fracture propagation phase with flow rates up to 100 lpm. Two cycles are used to reach high flow rates due to pump change at 35 lpm. Flushing is added to the high viscous gel injection protocol (Figure 3B).
  4. A pressure rate test to measure the stress normal to the created fracture

The breakdown pressure for HF3 was at 16.2 MPa. The jacking pressure measured 5.8 MPa and the final injectivity measured 0.88 l/min/MPa. The breakdown pressure for HF8 was at 21.1 MPa and the jacking pressure measured 5.0 MPa. The final injectivity measures 0.20 l/min/MPa. For all HF-experiments the injectivity increased 100 to 1000 times.

Preliminary Insights

1. HF connects to pre-existing fractures such that the fracture fluid leak-off. Further fracture propagation is led by hydraulic shearing due to hitting a pre-existing system. The effect of shearing is depended on the fluid (flow rate and viscosity) and the early stage fracture orientation/geometry.
2. Likelihood to create single flow path rather than flow volume.
3. Evidence for creating a temporary hydraulic connection to the fracture system that closes after stimulation.
4. The injectivities after HF are around 0.1 to 1 l/min/MPa. These are similar to the HS-experiments.
5. The prediction of E-W fracture propagation needs to be validated by the microseismic cloud and the opening along the foliation plane is yet not be validated by acoustic televiewer log.

References


Hydraulic fracture growth in previous experiments (Gischig et al., 2017)

- Figure 2: Hydraulic fracture growth in SBH3 borehole observed by micro-seismic monitoring
  - Small injection flow rates were used (1-5 lpm)
  - Impression packer show an opening along the foliation plane (157/75°)
  - Micro-seismic monitoring show fracture propagation in E-W direction

Motivation

Hydraulic fracturing (HF) is a common method to create artificial fractures to create new flow paths and to connect to pre-existing fractures. We aim to study injection parameters, such as injection flow rate and fluid viscosity, and their influence on fracture propagation, fracture geometry and micro-seismicity in crystalline rock.

The HF experiments are part of the in-situ stimulation and circulation project (Amann et al., 2017), which was recently carried out at the Grimsel Test Site.

Propagation mode of hydraulic fractures

- Numerical modelling has been used to study the size and mode (toughness or viscosity dominated) of the growing fractures
- A penny-shaped fracture geometry is assumed due to model calibration with hydraulic fractures during stress characterization phase.
- Definition of fracture toughness value for determining the asymptotes:
  \[ K = K' \times (\frac{\Delta \sigma}{\mu})^\delta \]

Viscosity dominated

- Injection of ~1 m³ fluid for each injection phase
- The injection protocol includes the following elements:
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References

Introduction

Research of the chair “Gaz Naturel” – Petrosvibri at the EPFL contributes to SCCER-SoE WP1: “DGE and CO₂ sequestration”. WP1 research focuses on problems for future realization of CO₂ storage in Switzerland. Proper assessment of carbon dioxide storage procedures allows to significantly reduce its concentration in the atmosphere and thus directly contributes to Swiss energy strategy 2050. The sound characterization of reservoirs and caprocks in Switzerland and the assessment of their potential for CO₂ storage is therefore fundamental.

In order to grant a safe injection of CO₂ into reservoir formations, the overlaying shaly caprock must perform efficiently. This work aims at identifying the relevant processes related to shale-CO₂ interactions and the impact of CO₂ injection on the mechanical properties of the material.

Experimental methodology

Cylindrical specimens of intact Opalinus Clay shale:
- height = 12.5 mm
- diameter = 35 mm

An advanced oedometric system (imposing zero lateral strain) is used (Figure 1).

Procedure for Test 1 and Test 2:
- Saturation in constant volume conditions;
- Pore water pressure increase to 7.3 MPa while maintaining constant vertical effective stress;
- Consolidation in steps to the desired stress state;
- CO₂ injection at liquid state (23°C, pressure up to 12 MPa);
- Mechanical compression up to 90 MPa of vertical total stress.

The stress paths of the tests are depicted below:

Vertical strain versus vertical effective stress during oedometric loading and during CO₂ injection at constant vertical effective stress.

Results and Discussion

Loading (test 1) and unloading (test 2) steps prior to CO₂ injection (black solid line), followed by the CO₂ injection phase (red line)

Strain induced by CO₂ injection is relevant at OCR = 1
⇒ material structure is more prone to collapse when it is found in normally consolidated conditions.

Details of the CO₂ injection phase:

Possible causes of strains induced by CO₂ injection:
⇒ Desaturation effects (CO₂ / pore water differential pressure)
⇒ Double layer effects induced by the diffusion of CO₂

Diffusion of CO₂ into the shale does not impact significantly the hydro-mechanical properties of the material, since no significant change in oedometric modulus and hydraulic conductivity are highlighted after the injection of CO₂.

The impact of CO₂ injection on the deformation behaviour of the material appears to be limited compared to the deformation behaviour induced by a mechanical loading.

Acknowledgement

V. Favero is an SCCER-SoE postdoctoral researcher. The tested shale is provided by Swisstopo.
Visualizing salt tracers using GPR


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Motivation

Hydraulic tracer tests are a powerful tool to characterize connections between subsurface locations, but the actual flow path remains unresolved. One potential method to investigate this is presented here and relies on Ground Penetrating Radar (GPR) and salt tracers. The experiments described here were conducted within the ISC project at the Grimsel Test Site (GTS).

Single-Hole Reflection GPR

The GPR reflection response is sensitive to electrical conductivity and permittivity. At interfaces with changing parameters, a signal reflection occurs. This way structural changes, i.e., shear zones, can be imaged.

For single-hole reflection GPR the transmitter and the receiver were moved with a fixed distance in the same borehole. Every 5 cm a trace is recorded, which adds up to a reflection image. The acquisition was performed with 250 MHz antennas in borehole GEO 3, indicated in red on the schematics. Amongst other reflections, the structures from the shear zones and the two injection lines are well visible in the data.

Salt Tracer for GPR

Salt water changes the electrical conductivity locally, hence induces a signal change. As salt water has a higher density than tap water, ethanol is added to achieve a neutrally buoyant tracer to achieve comparability with other tracer tests.

The tracer used here is composed of: 85 kg water, 21 kg ethanol and 45 kg of salt, which leads to a conductivity of 318 mS/cm. It was injected in injection line 1 of the GTS over a course of 90 min with tap water and two dye tracers injected before and after for later comparison.

Difference Imaging

The salt tracer only induces small changes in the GPR reflection image. To retrieve the tracer information, a reference image is acquired before tracer injection. The difference between the following measurements and the reference should leave only the tracer visible. Small variations in the data, especially time or phase shifts, have a large impact on the differences. The following processing steps were used to correct for these issues:

- Remove DC-Shift
- Time Shift
- Band-pass Filter
- Time Gain
- SVD First Arrival Removal
- Normalize Data
- dt-Drift Correction
- Spatial Realignment
- Differencing

Results

Difference images at increasing time from A to D. The borehole and shear zone reflections are mostly eliminated by the differencing. Artifacts on the top left of the images arise from effects in the tunnel.

A: Tracer not yet visible.
B: Tracer visible at injection point (indicated in A).
C: Tracer propagates.
D: Tracer propagates further and starts to vanish from dilution.

Conclusion & Outlook

The current state of the project proves that salt tracers can be used to monitor tracer movement using GPR. Together with additional information from hydraulic tracer tests, more information on the flow path, the media porosities and tracer velocities can be gained. In the future the GPR data with integration of hydraulic tracer test results will be used to generate a hydraulic model of the ISC project volume.

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A comparison of the seismo-hydro-mechanical observations during two hydraulic stimulation at the Grimsel Test Site


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***Centre for Hydrogeology and Geothermics, University of Neuchâtel, CH-2000 Neuchâtel

Stimulation interval HS4 at 27.2 - 28.2 m in borehole INJ2, S1 shear zone

Stimulation interval HS1 at 39.75 - 40.75 m in borehole INJ1, S3 shear zone

Injection strategy

Cycle 1.1: Pressure-controlled determination of initial injectivity, breakdown of rock
Cycle 1.2: Pressure-controlled, determination of jacking pressure
Cycle 2: Rate-controlled, actual stimulation
Cycle 3: Pressure-controlled determination of final injectivity and jacking pressure

Pressure monitoring

A total of 12 pressure observation intervals to record pressure evolution

Deformation monitoring

Longitudinal strain with fibre-optics sensors

Sensor depth

Deformation monitoring

Active + passive seismics

Systematic travel time changes in the stimulated volume
Variable number of seismic events

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Introduction

In-situ stimulation and circulation (ISC) experiment is a unique decameter stimulation experiment which was initiated at the Grimsel Test Site (GTS) in August 2015 (Amann et al., 2017). The main objective of the ISC experiment is improving our understanding of the thermo-hydro-mechanical and seismic (THMS) processes during hydraulic stimulation of crystalline rocks. In particular, we are interested in:

- The creation of sustainable heat exchanger via permanent hydraulic conductivity enhancement during high-pressure fluid injection
- Ways to reevaluate the ability to assess, model and control induced seismic hazard and risk.

A series of hydraulic stimulation tests had been executed as part of the ISC experiment to fulfill the objectives, which are (Figure 1, Table 1):

- Ten mini hydraulic fracturing (MHF) and one hydraulic testing in pre-existing fractures (HTPF) in SBH boreholes (September 2015)
- Six hydraulic shearing (HS) in INJ boreholes (February 2017)
- Six hydraulic fracturing (HF) in INJ boreholes (May 2017)

In this study, the effect of these multi-scale hydraulic stimulation on permeability enhancement and injectivity increment of the rock volume is studied.

Hydraulic Stimulation Mechanisms

Hydraulic stimulation describes two distinct but related mechanisms, which are

1. initiation and propagation of new fractures (mode I fractures), so-called hydraulic fracturing (HF), and
2. shearing of pre-existing fractures (mode II and III), i.e. hydraulic shearing (HS) (Figure 2).

The occurrence of dominant mechanisms depends on rock mass properties such as rock structure, orientation of existing structures such as fractures, faults, and foliation as well as the injection parameters (injection rate and fluid viscosity).

In reality, shearing as well as fracture formation and opening may occur concomitantly, and the distinction between them during injection is challenging. A major difference between HF and HS is the resultant permeability enhancement: for HF the permeability almost fully closes after depressurization, whereas for HS it is mostly reversible for HS as the fractures almost fully close after depressurization.

Permeability Changes During Stress Measurement

Ten mini hydraulic fracturing and one HTPF test were performed in three stress measurement boreholes, i.e. SBH3, SBH4, and SBH5 in order to estimate the orientation and magnitude of the principal stresses in the stimulated rock volume (Krietsch et al., 2017). To determine the impact of these meter-scale hydraulic stimulations in the SBH3 and SBH4 boreholes, permeability, porosity, and flow rate of each test were measured before and after the stress measurement using the conventional packer tests (Jalali et al., 2017).

References


A matlab package for thermo-hydraulic modeling and fracture stability analysis in fractured reservoirs

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Centre for Hydrogeology and Geothermics - University of Neuchâtel

Motivation

A large fraction of the world’s water and energy resources are located in naturally fractured reservoirs within the earth’s crust. Understanding the dynamics of such reservoirs in terms of flow, heat transport and fracture stability is crucial to successful application of engineered geothermal systems (also known as enhanced geothermal systems, EGS) for geothermal energy production in the future. The reservoir development characteristics such as permeability creation and induced seismicity largely depend on the traits of pre-existing fractures such as porosity, permeability and orientation within the local stress field. One of the primary driving mechanisms for permeability creation in EGS involves shear failure induced by fluid injection at high pressures.

Methods

We present and validate an implementation of an embedded discrete fracture model (EDFM) for single phase flow and heat transport with additional capabilities to determine fracture stability in fractured reservoirs.

The conceptual idea of the EDFM is the separation of a fractured reservoir into a fracture and a damaged matrix domain. A transfer function accounts for coupling effects between the two domains (Figure 1).

Fracture and matrix domains are computationally independent except for the transfer function. As the fractures are generally very thin and highly permeable compared to the surrounding matrix rock this allows for a lower dimensional representation of fractures.

Validation on crossing fractures

We compare our solution to a reference solution computed by COMSOL Multiphysics which is a widely used finite element package with subsurface flow and transport capabilities. The reference solution is computed on a conforming discrete fracture network where the matrix elements are aligned exactly on the grid with very high resolution.

We evaluate the coupled results of fluid flow and heat transport over 40 years.

Conclusion

We validated a fractured reservoir modelling framework implemented in matlab which can be used as a standalone simulation package for TH(M) case studies in geothermal reservoirs or as a blue print for the re-implementation of the method e.g. in a high performance computing (HPC) framework. This package will soon be made available to the scientific community as open source.
Introduction

Fault slip data inversion methods to estimate the in-situ stress are generally based on the Wallace-Bott hypothesis, stating that the slip on the fault plane occurs in the direction of the maximum resolved shear stress (Wallace 1951, Bott 1959). In this work we focus on validation of the Wallace-Bott hypothesis in the presence of the fluid point source that may induce slip reorientations. A multi-parametric study covering (i) fault geometry such as planar and non-planar faults, (ii) fault orientation, (iii) friction angle, (iv) dilation angles, (v) joint stiffness was performed to understand the effect of each parameter on the misfit angle between the simulated slip vectors and the resolved shear stresses in the presence of the fluid injection.

Methods

• Analytical solution from Bott (1959)
• Numerical solution using the 3D distinct element method (Figure 1)
  • linearly elastic, homogeneous, isotropic, deformable blocks
  • Coulomb slip model joint model
  • Active (fracture) and inactive (rock mass) parts of the joint
  • $\sigma_{xx} = 3 \text{ MPa}$, $\sigma_{yy} = 5 \text{ MPa}$, $\sigma_{zz} = 6 \text{ MPa}$; $p = 0.5 \text{ MPa}$
  • 8 increasing steps of 0.5MPa, starting with a 1 MPa initial pressure
  • Rake of the slipping vectors are compared to the analytical solution

Results

The fluid pressure and shear displacement vectors on the fracture are shown in Figure 2. Increasing fluid pressure decreases the effective normal stress and causes the elastic and subsequent plastic deformation of the model. The perturbation in stress in the vicinity of the fluid source is shown in Figure 3. It can be observed that the stress tensors (cross symbol) is altered by the increasing fluid pressure. After slip occurs, the minimum principal stress is rotating towards the direction perpendicular to the fracture opening due to shear stress release by slip on the fault plane.

Conclusion

• Slip orientation is controlled by the fault geometry and reduced stress tensor
• Fluid injection causes stress perturbation around the injection point
• Generally for a given far-field stress the fluid injection affects the mean misfit angle between the analytical and numerical solutions within the practical threshold (5°).
• Joint stiffness, dilation and friction angle are the key factors influencing the misfit angle. They should be investigated with more details to seek for generalization of the conclusion of this study

References

Tracer based characterization of the connected fracture volume in the DUG Lab at the Grimsel Test Site

A. Kittilä, K. Evans, M. Jalali, M. Willmann, and M.O. Saar
ETH Zurich

Background

Tracer tests were conducted at the DUG Lab at the Grimsel Test Site (GTS) as part of the ISC experiment (Amann et al. 2017) in order to characterize the connected fracture volume. A total of four tests were conducted, the first two before the hydroshock stimulation program and the second two a month after. Tests 1-3 featured injection into intervals of INJ2 with production from an interval in INJ1, a fracture zone in the AU gallery, and several intervals in PRP observation holes (Tests 2 and 3 only). These tests allow an assessment of changes to flow paths resulting from the stimulations. Test 4 featured injection into two intervals of INJ1 with production from Interval 4 of INJ2, the AU tunnel and the PRP intervals. In this test (and Test 1), novel DNA nanotracer particles were injected with the standard solute dye tracers. The DNA nanotracers provide additional information of the preferential flow paths and the accessible pore volume due to size exclusion.

Materials and Methods

In all four tracer tests, two distinct intervals in the injection hole were injected with two of four available solute dye tracers. The DNA nanotracers (Pausescu et al. 2013) were produced by the company Haelixa.

The environmentally friendly DNA-labeled silica particles allow the production of virtually unlimited number of uniquely identifiable tracers exhibiting the same transport properties.

Moment analysis (Shock and Forsmann 2005) was used to determine swept pore volume and flow-storage geometry from the individual recorded tracer concentration histories. First, the concentration histories are normalized to age distribution functions:

\[ E(t) = \frac{C(t)M_{in}}{M_{in}} \]

which are used to determine the swept volume:

\[ V_p = \frac{m}{M_{in}} \int_0^t E(t' \Delta t) \frac{dt'}{2} \]

Multi-rate mass transfer (MRMT) model (Hagerty and Gorelick 1995) implemented in random walk particle tracking (RWPT) method (Salamon et al. 2006) was applied to characterize the anomalous mass transport. In this approach, the medium is considered to contain overlapping mobile and immobile continua that exchange mass. Immobile zones with different properties can be assigned to account for the different total pore volumes swept by the solute and DNA nanotracers.

Comparison of flow/storage geometries of solute sulforhodamine B and DNA nanotracer named GR-3. Deviation from the diagonal is a measure of flow path heterogeneity, or channeling. In general, the DNA nanotracers experience more channeling, i.e., smaller pore volumes provide larger fractions of the total flow.

Discussion and Outlook

- The DUG Lab fracture volume was characterized by combining DNA nanotracer particles and solute dye tracers.
- Four tracer tests have been completed, each of which had two separate injections.
- The early termination of Tests 1-3 required undesirable data extrapolation. Future tests should be continued for a longer time.
- The DNA nanotracers arrived invariably earlier than the solutes.
- The results show that the swept volume of the DNA nanotracers is about a tenth of that from the solute tracer for the same injection-production pairs.
- Indications of multiple preferential flow paths are seen in several recorded tracer signals.
- The on-going analysis with the MRMT model is ongoing.
In situ characterization of groundwater flow and heat transport in stimulated fractured network using DTS

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ETH Zurich, Geological Institute, Zurich, Switzerland

**Objectives**

Stimulation and Circulation (SCC) experiment at the Grimsel Test Site is dedicated to study seismo-hydro-mechanical coupled processes relevant for the development of a sustainable nuclear waste exchange in low permeability crystalline rock under controlled conditions. Distributed Temperature Sensing (DTS) technology offers great promise for locating discrete fractures and measuring their hydraulic and heat exchange properties. We use Active-DTS tests and cross-borehole thermal tracer tests to investigate groundwater flow and heat transport in fractured media before and after hydraulic stimulation.

**Active-DTS Experiment**

In A-DTS, the electrical heating cable [2, 3] or borehole fluid [4, 5] is heated. The temperature response along the FO cable deployed in the middle of the borehole during the heating and subsequent cooling allows:
- In situ determination of rock thermal properties.
- Fracture detection.
- Characterization of fracture inflows.

**Cross-borehole thermal tracer test**

A cross-borehole thermal tracer test is analyzed to identify fractures in heat transport and to measure thermal breakthrough curves in multiple observation points located at different distances from the injection point. The subsequent analysis of the measured breakthrough curves may provide new insights on flow channeling as well as fracture geometry [6].

**Conclusion**

Our study confirms that FO DTS enables investigation of hydrogeological processes with high spatial and temporal resolution. In particular DTS technology in active mode allows fracture detection and characterization of fracture hydraulic properties similar to fluid conductivity logs. The advantage of this ADTS compared to the classical fluid conductivity logging is that:
- no salt is added to the system
- measurements are conducted without logging-induced mixing
- Cross-borehole heat tracer tests allow to understand heat transport processes in fractured media. Conduction of tests before and after hydraulic stimulation allows to quantify the effect of hydraulic stimulation on heat exchange properties of the media.

**References**


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**Distributed Temperature Sensing at Grimsel Test Site (GTS)**

DTS uses the Raman backscatter characteristics of light emitted following a laser pulse into a fiber optic cable to determine the distributed temperature along fiber with a spatial resolution of a few micrometers and temporal resolution of several seconds. At GTS several boreholes were equipped with distributed temperature-sensing optical fibers that are grouted in place. The bottom-piece and the connection points of the DTS/injection rod are visible in the cartoon. DTS principle based upon Raman backscatter detection is shown in the cartoon. A fiber optic cable is deployed in a double-ended setup [1].

**Results**

- **Figure:** Schematic of DTS principle based upon Raman backscatter detection. In this cartoon, a fiber optic cable is deployed in a double-ended setup [1].
- **Figure:** DTS measurements during the thermal tracer test conducted before the hydraulic stimulation. In plane view of thermal anomalies measured in observation boreholes and after hydraulic stimulation in INJ 2.
- **Figure:** DTS measurements in PRP 1 and PRP 2 boreholes during the thermal tracer test conducted before the hydraulic stimulation.
- **Figure:** DTS measurements in PRP 1 borehole during the thermal tracer test conducted after the hydraulic stimulation.
- **Figure:** DTS measurements in PRP 1 and PRP 2 boreholes during the thermal tracer test conducted after the hydraulic stimulation.
- **Figure:** Schematic of Active-DTS method in a well intersecting two transmissive fractures. Heating and cooling data can be used to infer thermal properties of the formation as well as groundwater flow.
**How much can we interpret mineral surface area with distributions of minerals and pores?**

Xiang-Zhao Kong1,*, Jin Ma1, Duncan Webster2, Martin O. Saar1

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**Introduction**

Fluid-rock reactions play an important role in many geo-engineering processes, such as Enhanced Geothermal Systems (EGS) and Carbon Capture, Utilization, and Storage (CCUS). These reactions may change the reservoir permeability dramatically by mineral precipitation and/or dissolution:

- Unfavorable reactions can lead to a significant decrease of reservoir productivity/injectivity in EGS and CCUS
- Favorable reactions can lead to a higher heat productivity in EGS or facilitate long-term CO2 mineral trapping in CCUS

However, the progress of these reactions depends on individual mineral accessible surface areas that are in general poorly constrained for natural geologic samples, in general, reactive surface area is estimated using methods including geometric model, Brunauer–Emmett–Teller (BET) gas adsorption method, batch and flow-through experiments and imaging techniques based on the principle of stereology. In this study, we take the advantages of both BET method and imaging techniques to determine accessible reactive surface areas of individual minerals. These measurements will be later calibrated in future flow-through experiments.

**Sample characterization**

The rock samples used in this study are sandstones from a depth of 9546.6 m from Geothermal well Vydmanin-1, located at the Northeast coast of the Baltic Sea of Lithuania. A thin section microscopy image (Figure 1) indicates an average grain size of 65 μm - 250 μm.

The rock composition (Table 1) was determined using XRF, XRD, and SEM imaging analysis. Chemical compositions of individual minerals were determined by quantitative SEM chemical analysis.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Average chemical formula</th>
<th>wt%</th>
<th>vol%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolomite (Dol)</td>
<td>CaMg3(PO4)2</td>
<td>2.84</td>
<td>12.26</td>
</tr>
<tr>
<td>K-feldspar (Kfs)</td>
<td>NaA1(Si3O10)(Al2O3)</td>
<td>2.96</td>
<td>11.62</td>
</tr>
<tr>
<td>Muscovite (Mus)</td>
<td>KAl3<a href="OH">Si3O10</a>2</td>
<td>2.82</td>
<td>5.48</td>
</tr>
<tr>
<td>Kaolinite (K)</td>
<td>Na2O·Al2O3·2SiO2·2H2O</td>
<td>2.60</td>
<td>0.94</td>
</tr>
<tr>
<td>Emerdenite (Em)</td>
<td>Fe2Ti5O12</td>
<td>4.72</td>
<td>0.23</td>
</tr>
</tbody>
</table>

The volume fraction of individual minerals calculated from SEM images agree well with XRF and XRD results (Table 1). This promotes the usage of further image analyses for mineral accessible surface area.

**Pore size distribution (PSD)**

The pore-size distribution (PSD) (Figure 3) was analyzed using three methods, including mercury (m) intrusion porosimetry, analysis of SEM-BSE (1.2 μm) and 3D CT (191 μm) images. In general all measurements agree well with each other. The discrepancies are very likely introduced by the difference in measuring principles (pore throat size during mercury injection methods and pore size during imaging process). In 3D CT analysis, due to limited resolution, most pores have been filtered out and only ~16% pores (relatively large) remain visible. However, there is still a good match between results for the 2D and 3D image analyses. This provides a positive validation for the stereological method used in this study.

**Reactive surface area analysis**

To minimize the resolution mismatch between the SEM-BSE and the SEM-EDS images, minerals are grouped into 3 different types (Figure 5). Then corrections for each group were applied to reduce the relative difference of the perimeter density from 40.0% to 2.9%.

Mass-specific surface area (SSA) of whole rock samples was measured by the BET method with nitrogen as the adsorption gas at a temperature of 77.3 K. A bulk mass-SSA = 1.447 m2/g was obtained by using a 5-point method with a correlation coefficient of R² > 0.9995.

Perimeter density (m/m), i.e., the ratio between solid perimeter and solid area, was first calculated using the SEM-BSE binary image (Figure 2b). Based on the principle of stereology (Webel, 1969), mass-SSA (m2/g) was then the product of a bias correction factor of 4/n, the reciprocal of rock density that is measured to be 2.11 g/cm3, and the perimeter density. The stereological analyses on both the SEM-BSE image (Figure 2b) and the SEM-EDS image (corrected) yield mass-SSA values of 0.031 m2/g and 0.032 m2/g respectively.

Roughness correction was also applied to individual minerals such that a good match to the BET measurements of the sample SSA can be achieved. Table 2 shows the BET literature values for pure individual minerals, accessible surface areas and their fractions before and after the corrections with different correction factors listed in Table 2. Compared to literature values, our SSA values for individual minerals are reasonable. The bulk SSA, i.e., the overall accessible SSA of all minerals, is then calculated to be 1.441 m2/g, i.e., close to the bulk BET measurement (1.447 m2/g).

**Conclusions**

We have quantified porosity and pore-size distribution (PSD) of rock samples, using a Helium gas pycnometer and Hg porosimetry, respectively. Rock compositions are determined by a combination of XRF, XRD, and SEM-EDS, which are later geometrically mapped onto 2D images derived from SEM-BSE. The stereological method used in this study is validated through comparisons of mineral volume fraction, porosity, and PSD results from image processing and laboratory measurements. Normalization of stereological SSA to BET measurements yields roughness corrections of individual minerals. Due to the computational expense of 3D micro-CT analysis, 3D reactive surface area analysis is still on-going and will be presented in our peer-review paper.

**Acknowledgements**

This work is supported by an European project entitled “Demonstration of soft stimulation treatments of geothermal reservoir project” (BESTRESS), funded by European Union’s Horizon 2020 research and innovation program under the grant agreement No.691728. The rock sample is provided by Geoerma, a Lithuanian geothermal energy company. The 3D micro-CT analysis was performed by Dr. Duncan Webster at SCANCO Medical AG, Zurich, Switzerland.

The Geothermal Energy & Geofluids (GEG) group is endowed by the Werner Siemens Foundation, which is hereby gratefully acknowledged. The GEG group is also a research partner of SCCER-SoE, Switzerland.
Geological characterization and in-situ stress state of the ISC experimental volume

H. Krietsch, V. Gischig, F. Amann, J. Doetsch, M.R. Jalali, B. Valley

Motivation

The In-Situ Stimulation and Circulation (ISC) experiment has recently been carried out at the Grimsel Test Site (Amann et al., 2017). It includes six hydro-shearing and six hydraulic fracturing experiments. A precise geological model and detailed knowledge of the in-situ stress state is crucial for the analysis and interpretation of the hydromechanical response of the experimental volume to high-pressure fluid injection. For this purpose an extensive geological characterization combining tunnel-mapping, core- and geophysical borehole logging (OPTV, ATV, FWS) was conducted, in combination with detailed geophysical surveys (i.e. GPR and seismic tomography). Additionally, a comprehensive stress measurement campaign, including overcoring (USBM & CSIRO HI) and hydraulic fracturing was carried out (Gischig et al., 2017; Krietsch et al., 2017).

Geological Model

The precise locations and orientations of shear zones and fractures were mapped using geophysical borehole and core logs. In total five shear zones are identified: three S1 (strike N52°E) and two S3 (strike N93°E) shear zones. The three S1 shear zone are characterized by an increase in foliation intensity. The two S3 shear zones are localized in one metabasic dyke, each, and separated by 25 m. Additionally, information about fracture density are gathered. As the boreholes approach the shear zones, the fracture density increases from 0-3 frac/m (host rock) to 14-22 frac/m. The magnitudes for the ‘far-field’-tensor range from 13.1 to 14.4 MPa for $\sigma_1$, 9.2 to 10.2 MPa for $\sigma_2$, and 8.6 to 9.7 MPa for $\sigma_3$. A drop in principal stress magnitudes was observed, as the measurements approached the shear zones.

Stress measurements

Two stress field solutions were found: one for the ‘far-field’ and one close to the shear-zone. The orientations obtained from USBM, CSIRO-HI and HF are consistent for each tensor.

Combination of geology and stress field

Based on the ‘far-field’ tensor the slip and dilation tendencies of all mapped geological structures were calculated. S1 shear zones have the highest slip tendencies, and S3 shear zones the highest dilation tendencies.

References


Deformation and tilt measurements during the ISC experiment at the Grimsel Test Site
H. Krietsch, V. Gischig, B. Valley, F. Amann

Motivation
A decameter scale stimulation experiment, including six hydraulic shearing (HS) and six hydraulic fracturing (HF) experiments, has recently been conducted at the Grimsel Test Site. One aim was the quantification of the spatial mechanical response during high pressure fluid injections into a pre-existing fracture network and intact rock mass. Multiple Fibre Bragg-Grating (FBG) sensors, distributed fibre optics strain systems (DBS) and tiltmeters were installed to monitor the deformations. In this contribution we present exemplary results from HS and HF experiments.

Sensors
A total of 60 FBG sensors were distributed in three differently oriented boreholes, covering intact rock and various fractures. The sensors average the strain over a 1 m baselength, and have a resolution of 0.1 µstrain and accuracy of 1 µstrain. Additionally, two DBS chains with a resolution of 1 µstrain and accuracy of 10 µstrain, covering three boreholes, each, were installed. At the tunnel west of the experiment, three tiltmeters were installed measuring the deviation from horizontal in two axes with a sensitivity of 0.1 µradians.

DBS strain measurements
Compared to the FBG sensors, the DBS have a resolution too low to precisely monitor the deformation due to the stimulations. In each borehole, one leg was packed (i.e. distinct base length of 0.6 m) and one leg was bare. The measurements indicated that the packed leg is more accurate than the bare one, but still of lower quality than the FBG recordings. For the description of the spatial mechanical response during the stimulation, the DBS is used in a qualitative way. In the PRP boreholes the movement of the packer due to an increase in interval pressure is visible in the strain data. During HF8 the hydrofrac propagated through the resin (yellow) above interval 1 in PRP2, which can be seen in the DBS.

Tilt measurements
Tilt measurements are as additional constrain for the orientation of stimulated shear zone. The tilt signal need to be corrected for the tunnel free surface effects with help of numerical modeling.

Figure 1. Sensor locations in the test volume: a) 20 FBG-sensors per borehole, b) FBS (red) and PRP Boreholes (green) with one loop per group, c) Position of three tiltmeters in VE-tunnel west of volume.

Figure 2. Exemplary borehole design for FBG-sensor.

Figure 3. Transient strain signals in FBS3 during HS1 experiment. The strain signals indicate different behaviour depending on borehole orientation and sensor locations.

Figure 4. Maximum recorded strains during HS1 experiment. The strain signals indicate different behaviour depending on borehole orientation and sensor locations.

Figure 5. Schematic interpretation of the HS1 experiment, with indicated shear sense along S1 shear zones.

Figure 6. Comparison between FBG sensors, packed and bare leg DBS measurements in FBS1. Data represent strain at specific point over time.

Figure 7. Distributed strain signals in PRP boreholes. Strong influence of packer movement can be observed. Above interval 1 in PRP2 a hydrofrac propagated through the resin.

Figure 8. Tilt movement in X- and Y-direction. EW tilt (Y) indicates expansion of test volume. NS tilt (X) is sensitive to shear zone orientation and injection location. HS1 and HS4 indicate different behaviour in X-tilt, due to different orientation of shear zone, and different location of injection interval.

Figure 9. Geometry of tilt model. Normal opening of penny-shaped fracture with different orientations.

Figure 10. Modelled influence of the tunnel on the tilt-field. Difference displacement represents ratio tunnel/rock mass displacement.
Core-scale reactive transport modelling of injection of CO$_2$-charged brine into natural sandstone

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Introduction

Fluid-rock reaction is an important process involved in many geological and geo-engineering systems such as chemical stimulation of enhanced geothermal systems (EGS) (Poiler et al., 2009) and carbon capture, utilization, and storage (CCUS) (Guas, 2010; Xu et al., 2003). These reactions lead to mineral dissolution and precipitation which may cause changes of reservoir porosity and permeability (Cai et al., 2009; Nogues et al., 2013). Due to the complexity of coupled fluid flow and fluid-rock reactions in heterogeneous porous media, it is challenging to predict long-term operation performance of geothermal reservoirs.

Geochemical transport modelling is well recognized as a powerful approach to probe the physical and chemical evolution of subsurface systems (Beckingham et al., 2016). In this study, a 1D core-scale reactive transport model is developed to simulate the injection of CO$_2$-charged brine into a natural sandstone core. We present the simulation results using calculated ion concentrations to interpret mineral dissolution/precipitation reactions in a multi-mineral system.

Model description

We employed PFLOTRAN to perform a 1D core-scale reactive transport simulations at an outlet pressure of 10 MPa and a temperature of 40 °C. We modelled an injection of CO$_2$-rich brine at a constant volumetric flow rate of 2 ml/min into a cylindrical sandstone specimen with a length of 3.9 cm and a cross section area of 5.29 cm$^2$ as shown in Figure 1. The NaCl concentration of the injected fluid is 1 mol/l, and 0.8 mol/l CO$_2$(aq) was dissolved into it to reach 80% of CO$_2$ solubility at such simulation conditions.

The rock properties in this model follow a sandstone sample from the geothermal reservoir, Vydymantal (954.6 m deep), Lithuania. Its porosity is measured to be 0.22 using He pycnometer and permeability 300 mD using flow-through experiments. The sandstone composition is listed in Table 1. Other parameters, such as mineral volume fraction and reactive surface area, take the results from analysis of SEM-EDS image (Figure 2). Mineral reaction rate constants are taken from Palandri et al. (2004).

Results and discussion

In the following, we only show the concentration of Ca$^{++}$, because Ca$^{++}$ and Mg$^{++}$ only exists in dolomite with a mole ratio of 1:1. Figure 3 shows major ion concentrations at PV=0.53 and PV=793. Concentration of Na$^+$ does not change much during the whole simulation. The simulation results show that when the volume of the injected fluid is less than one total pore volume (PV) of the core, ion concentrations clearly indicate a diffusion-controlled reaction front from 12 mm to 24 mm. At PV=0.53, compared to other cation (K$^+$, Fe$^{++}$, Al$^{+++}$, and SiO$_2$(aq)) concentrations, Ca$^{++}$ concentration is not affected by the dilution (mixing) at the inlet because of relatively high reaction rate of dolomite. When the injection volume of fluid is more than one pore volume (PV>1), a sharp concentration front is developed due to depletion of minerals, in particular for dolomite. This concentration front is migrating towards the outlet with a speed of 0.0174 mm/PV. Figure 3 shows a typical front pattern at PV=793 where Ca$^{++}$ concentration is nearly zero from the inlet to the front, followed by a dramatic increment after the front.

Figure 4 shows the saturation index (SI) and the relative change of volume fractions of 5 major minerals in the system at both PV = 0.53 and PV = 793. When PV<1, volume fraction of most minerals do not change, except dolomite due to its high reactivity. The SI profiles indicate a potential dissolution of K-feldspar and a potential precipitation of kaolinite. When PV >1, similar to the concentration profiles, a sharp front is formed at the reaction front. Behind the front, all major minerals stay under-saturated, except for quartz which is closed to equilibrium. At the reaction front, muscovite and kaolinite quickly reach over-saturation but then are back to the equilibrium vicinity. Dissolution of K-feldspar and precipitation of kaolinite along the whole core is suggested.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
<th>Volume fraction (%)</th>
<th>Reactive surface area (cm$^2$/cm$^3$)</th>
<th>Rate constant (mol/cm$^2$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>SiO$_2$</td>
<td>46.0</td>
<td>1521.4</td>
<td>1.0 x 10$^{-13}$</td>
</tr>
<tr>
<td>Dolomite</td>
<td>CaMg(CO$_3$)$_2$</td>
<td>12.0</td>
<td>1328.7</td>
<td>3.0 x 10$^{-4}$</td>
</tr>
<tr>
<td>K-feldspar</td>
<td>KAlSi$_2$O$_4$</td>
<td>10.0</td>
<td>180.5</td>
<td>1.0 x 10$^{-2}$</td>
</tr>
<tr>
<td>Muscovite</td>
<td>KAl$_2$Si$_4$O$<em>10$(OH)$</em>$_2$</td>
<td>5.0</td>
<td>1310.0</td>
<td>1.0 x 10$^{-6}$</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>Al$_2$Si$_2$O$_5$(OH)$_4$</td>
<td>5.0</td>
<td>26087.2</td>
<td>5.0 x 10$^{-6}$</td>
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<tr>
<td>Ilmenite</td>
<td>FeTiO$_3$</td>
<td>0.3</td>
<td>100.2</td>
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</tbody>
</table>

Acknowledgement

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Mixed finite element method for recovering stress and displacement fields

Morteza Nejati, Thomas Driesner
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Introduction

Stresses and displacements computed directly from the finite element solution of geomechanical problems can be extremely inaccurate when using low order finite elements such as two-noded line element, three-noded triangular element, and four-noded tetrahedral element. These elements are extremely efficient in terms of computation cost, and therefore their use in large geomechanical models is of interest. Stress and displacement recovery methods are designed to improve the accuracy of low order elements for two main reasons: (i) To obtain better estimates of the stress and displacement throughout the domain, and (ii) To provide a benchmark for discretization error estimation which is useful for efficient mesh generation and mesh adaptivity. Previous methods solely focus on stress recovery and are based on polynomial choices outside the ones provided from finite element shape functions. Recovery by equilibrium in patches [1], recovery by compatibility in patches [2], and recovery by enhanced equilibrium in patches [3] are examples of these methods. In this research, a new method called recovery by enhanced compatibility and equilibrium is proposed, which is able to recover displacements as well as stresses, and it only uses the polynomials available from isoparametric element types to enhance the accuracy of the field variables.

Methodology

The two main variational theorems in the theory of elasticity are principle of minimum potential energy, and principle of minimum complementary energy. Minimum potential energy is based on a functional of displacement, where compatibility conditions are satisfied as priori by assuming a continuous displacement over the entire domain and permitted variation of displacement which satisfies the prescribed displacement boundary conditions. This variational equation gives the equilibrium equations. Minimum potential of complementary energy is a functional of stresses, where equilibrium condition is satisfied as priori by assuming equilibrated stresses with body forces and permitted variation of stresses. This variational equation is equivalent to the compatibility of displacements. In these two principles, one of equilibrium or comparability is assumed over the domain, while the other condition is satisfied by the variational equation. Reissner [4] defined a variation theorem in which neither compatibility nor equilibrium is assumed as priori, whereby both equilibrium and comparability are outcomes of the variational equation. This mixed variational theorem does not favor equilibrium over compatibility or vice versa, and permits simultaneous use of an assumed stress field and an assumed displacement field.

Let $\sigma_{ij}$ and $u_i$ be the components of the assumed stresses and displacements, respectively. The Reissner functional $\Pi_E$ is defined in terms of assumed independent stresses and displacements as:

$$\Pi_E = \int_\Omega (\sigma_{ij} S_{ij} - F_{ij}) d\Omega - \int_{\Gamma_T} T_ik dt - \int_{\Gamma_D} (u_i - \bar{u}_i) F_{ij} dt$$  \hspace{1cm} (1)

Here $S_{ijkl}$ denotes the components of the fourth-order elasticity matrix, $F_{ij}$ is the body force component, $\Omega$ is the domain of interest, and $\Gamma_T$ and $\Gamma_D$ are the traction and displacement boundary conditions applied along $\Gamma_T$ and $\Gamma_D$. After the finite element solution with low order elements is performed, the displacements are obtained and can be used as the boundary values for single or a patch of elements to solve for more accurate stresses and displacements using the mixed finite element. Let us assume that $F_{ij} = \tilde{F}_{ij}$ on $\Gamma_T$. The variation of the functional in Eq. (1) with respect to displacement and stress gives:

$$\int_\Omega \delta \sigma_{ij} (\sigma_{ij} + F_{ij}) d\Omega = 0$$

$$\delta u_i \left( \sum_{j,k} \sigma_{ij} S_{jk} u_k - F_{ij} \right) d\Omega + \int_{\Gamma_T} \delta \tilde{T}_i dt = 0$$ \hspace{1cm} (2)

By simultaneously solving these two equations for the displacement and stress, highly accurate recovered fields can be obtained.

Results and discussion

Figure 1 compares recovered values against the directly calculated ones as well as the exact values for a one-dimensional model. Figure 2 also shows how the order of convergence increases by using different orders of polynomials for the recovered estimates. These result show that the proposed method is highly efficient in recovering FE values with low accuracy. This is in particular important for efficiently modeling large thermo-hydro-mechanical systems with low-order elements.

References

Before EGS: In-situ Geothermal Gradient

Geothermal gradient is a key reservoir characteristic in determining how deep a well must be drilled to reach a certain temperature. However, faults and fractures in these rocks may facilitate natural convection: the process by which thermally-induced density differences of water cause cold, dense water to cycle deeper into the basement while hot, light water moves towards the surface. This can result in spatially varying temperatures around the upward/downward flowing plumes and can dramatically influence produced fluid temperature. This research seeks to better understand the role of natural convection in fractures on temperature variations in the subsurface and its implications for geothermal energy. We use the Complex Systems Modeling Platform (CSMP++), a reservoir modeling platform developed in part at ETH Zurich.

Numerical Modeling of Natural Convection in Fractured Media

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Flow Patterns Around a Single Fracture

Convection within a fracture also induces fluid flow in permeable host rocks. Two forces drive fluid flow around the fracture:

- Circulation of fluid in the fracture drives fluid inflow/outflow through the fracture walls
- The convection-driven thermal perturbation heats/cools fluid near the fracture, inducing buoyancy-driven fluid flow in the host

The combination of inflow/outflow (flow perpendicular to fracture face) and buoyant forces (vertical flow) creates secondary convection cells that circulate parallel to fracture strike (in the 0.7 and 1.0 mm cases).

Thermal Perturbation from Convection in a Single Fracture

As fluid at the bottom of a fracture is heated, it rises through the highly permeable fracture, carrying heat to the top of up-flow zones, while cold fluid sinks and cools the rock at the bottom of down-flow zones. The spacing and strength of these up- and down-flow zones are primarily a function of fracture aperture/permeability. Complex 3-dimensional thermal perturbations form around the fracture. Heating patterns above the fracture may be indicative of individual, wide convection cells or multiple narrow cells along a fracture in the subsurface.

Multiple Heterogeneous Fractures

Real fractures have heterogeneous aperture distributions, creating regions of high or low permeability. This influences the location and strength of natural convection cells. Additionally, fractures typically occur in sets of multiple fractures with similar orientations. The thermal perturbation caused by natural convection affects convection patterns in neighboring fractures, creating a “synchronization” effect – up-flow and down-flow regions will self-organize and create convection “rolls” across multiple fractures.

Conclusions and Future Work

Fundamental understanding of thermal perturbations created by convection within a fracture aids us in understanding subsurface fracture and flow networks. Additionally, further insight may be gained by accounting for more complicated physical processes (e.g. thermomechanics), modeling site-specific geometries, and by investigating optimal well placement in such a setting.

References

Motivation

The utilization of deep geothermal energy is impeded by the high drilling costs, which account for more than 40% of the total investment for a geothermal power plant [1]. Currently employed drilling methods are based on mechanical abrasion and exportation of the rock, resulting in substantial drill bit wearing and low rates of penetration (ROP) in hard rocks.

A novel approach is to implement a thermal assistance at the front face of the drill bit to enhance the performance of conventional rotary drilling and reduce the overall costs.

Concept

A hot-jet is used to thermally assist the conventional drilling by inducing shock heating and therefore thermally weakening the rock material. The material exportation would therewith require lower forces on the drill bits which also implies reduced drill bit wearing.

Combined thermo-mechanical drilling

The combined drill head features:

- Fuel (methane) and oxidizer (air) used as reaction fluids
- A combustion chamber where the fluids are combusted
- The drilling mud is also used to cool down the combustion chamber
- At the bit face a flame slot is prescribed
- Conventional cutters are placed next to flame-jets

Preliminary experiments

In order to evaluate the weakening effects of high heating rates-flame treatments, the strength after heating of Rorschach sandstone and Central Aare granite are analyzed. Different heating rates are studied to highlight the different behavior of the rocks after oven and flame heating.

Conclusions

The feasibility of the combined drilling method was demonstrated by means of the strength reduction after treating the rock with a flame-jet. Thus, local and high heating rate flame treatments can be implemented to weaken the rock material yielding lower forces on the drill bits and therefore increased performance and reduced drilling costs.

Additionally, the shielding of the flame is fundamental to allow this method to be effectively applicable and to be used in the field as an alternative drilling approach.

As a final step, the technology shall be implemented in order to finally prove the applicability and the related improvements in terms of drilling performances.

References


Pico-seismicity during hydraulic stimulation experiments at the Grimsel Test Site

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Introduction

The In-situ Stimulation and Circulation (ISC) experiment at the Grimsel Test Site (GTS) is an ongoing interdisciplinary project to study the pressure, temperature and stress changes in the rock mass due to hydraulic stimulation (Amann et al., 2017). In early 2017, the project entered the second phase, which included the main stimulation experiments. It involved high-pressure fluid injections into two shear zones (S1, S3) along which slip was induced (i.e. hydraulic-shearing). In May 2017 the second series of these experiments followed. These experiments involved injection at even higher pressures and larger flow rates which induced tensile-dominant fracturing (i.e. hydraulic fracturing). The entire experiment series was established to support research related to deep geothermal energy which should play a significant role in the Swiss energy mix by 2050 (Swiss Energy Strategy 2050).

Six sections (HS02, 04, 05, 03, 08, 01) of 1 to 2 m length distributed over the two injection boreholes were stimulated during the hydraulic shearing experiments (HS). Six different sections in intact rock within the same boreholes were stimulated during the hydraulic fracturing experiments (HF). During the experiments a multi-sensor monitoring system was in place: Deformation monitoring at boreholes, pressure monitoring boreholes, and streaming potential monitoring within drill holes. The figure below shows an overview of the seismic monitoring network installed during the performed experiments at GTS. The intervals stimulated during experiment HS01 and HS04 are highlighted in red.

Seismic monitoring network at GTS

The figure below shows an overview of the seismic monitoring network installed during the performed experiments at GTS. The intervals stimulated during experiment HS01 and HS04 are highlighted in red.

Overview hydraulic-shearing experiments

Only the HS experiments are considered in this poster. In the following, injectivity increase of all HS experiments estimated from the slope of injection pressure vs. flow rate at low pressure during step-pressure tests are stated. Experiments show a high variety in seismic response as well as in injectivity gain even though the injection protocol was similar and the amount of injected volume was similar for all experiments. The stimulation of shear zone S3 generates a much higher seismic response compared to injections into shear zone S1. The In-situ Stimulation and Circulation (ISC) experiment at the Grimsel Test Site (GTS) is

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Injection interval</th>
<th>Structure</th>
<th>Initial injectivity</th>
<th>Final injectivity</th>
<th>Change in injectivity</th>
<th>Volume</th>
<th>Total events</th>
</tr>
</thead>
<tbody>
<tr>
<td>HS02</td>
<td>38.5 – 40.0</td>
<td>51</td>
<td>0.218, 1.43</td>
<td>0.89</td>
<td>0.678</td>
<td>3100</td>
<td>12000</td>
</tr>
<tr>
<td>HS04</td>
<td>27.3 – 38.3</td>
<td>53</td>
<td>0.8, 0.9</td>
<td>1</td>
<td>1283</td>
<td>5686</td>
<td></td>
</tr>
<tr>
<td>HS05</td>
<td>21.8 – 32.5</td>
<td>52</td>
<td>0.89, 0.4</td>
<td>5</td>
<td>1211</td>
<td>2482</td>
<td></td>
</tr>
<tr>
<td>HS02</td>
<td>34.3 – 35.5</td>
<td>51</td>
<td>0.89, 1.7</td>
<td>406</td>
<td>851</td>
<td>314</td>
<td></td>
</tr>
<tr>
<td>HS05</td>
<td>22.0 – 32.9</td>
<td>51, 52</td>
<td>0.82, 0.3</td>
<td>270</td>
<td>1250</td>
<td>3782</td>
<td></td>
</tr>
<tr>
<td>HS01</td>
<td>38.8 – 40.8</td>
<td>51</td>
<td>0.809, 1.11</td>
<td>1000</td>
<td>982</td>
<td>508</td>
<td></td>
</tr>
</tbody>
</table>

Event evolution during hydraulic shearing experiments

This section shows, flow rate, injection pressure and cumulative number of seismic events for experiment HS01 and HS04. During HS01 shear zone S1 and during HS04 shear zone S3 was stimulated. Events which are detected at all 8 borehole stations (R16 – R23) and more stations in the surrounding tunnels contribute to the cumulative number of events of coinc. 8. Events which are detected at 7 borehole stations and other surrounding stations contribute to coinc. 7 and so forth. The vertical stripes on top of the “cumulative number of events” line indicate performed seismic surveys during which the search for induced seismic events was suspended. All experiments show, after breakthrough of the respective interval, a threshold pressure which has to be reached to initiate seismicity. Some seismic events are initiated after shut-in. Also the subsequent venting phase initiates seismic events.

Location of seismicity during experiment HS04

The figure below shows the absolute location of 1000 events of experiment HS04 in a view towards North (A), a view towards West (B) and in top view (C). The highest accuracy in location is thereby achieved by locating the events of coincidence level 8. The error in location increases with decreasing coincidence level (i.e. with decreasing detection quality). The location of the presented events was performed using manually picked P-wave arrivals in a homogeneous and isotropic velocity model having a P-wave velocity of 1560 m/s. The relative magnitude (Mr) stated was determined from recorded peak amplitudes of the respective event.

Conclusion and Outlook

- The performed hydraulic-shearing experiments show high variability in injectivity gain as well as in seismic response. Exceeding a specific injection pressure onsets seismicity. Induced seismic events tend to form clusters in both spatial distribution and magnitude.
- In a next step, event location will be performed for all 12 experiments with more advanced location techniques (e.g. joint hypocenter determination), additionally location accuracy will be quantified.

Reference


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An Implicit Level Set Scheme to simulate planar 3D hydraulic fracture propagation

Haseeb Zia, Brice Lecampion

Motivation

Hydraulic fractures are tensile fractures that propagate in an initially stressed rock due to the injection of fluid at a given rate. Simulating the propagation of such fractures is a challenge as there are multiple processes involved that are operating at multiple scales. Numerically capturing these processes on the full range of both temporal and spatial scales is challenging and has been the subject of many studies in the last few decades. The Implicit Level Set Algorithm (ILSA) [Peirce & Detournay 2008] is one such numerical scheme that aims at resolving these multiscale processes with relatively low computational cost. We present here an open-source Python implementation of this scheme.

ILSA Scheme

The Implicit Level Set Algorithm (ILSA) simulates the propagation of planar 3-dimensional hydraulic fractures. The solution of elasticity and the fluid flow is obtained in a fully coupled manner. The propagation is tackled combining a level set scheme and the hydraulic fracture tip solution [Garagash et al 2011]. The following numerical techniques are used to solve the coupled problem:

- Finite Volume method for the fluid flow
- Displacement discontinuity method for elasticity
- Level set method to track the fracture front

The scheme uses a Cartesian grid. The main strength of the scheme is its utilization of the plane-strain semi-infinite hydraulic fracture solutions to capture the near-tip behaviour. This allows it to compute the solution on a relatively coarse grid, making it both accurate and computationally efficient.

Governing Equations

The following equations describe the process of hydraulic fracture propagation.

- Elasticity for planar mode I fracture can be re-written as the following boundary integral equation
  \[ p = p_f - \sigma = -\frac{E}{8\pi} \int_{\Gamma_f} \frac{u(x', y')}{|x' - x|^2 + |y' - y|^2/2} \, dA(x', y') \]

- Fluid continuity:
  \[ \nabla \cdot q + g_L = Q(x, y) \delta(x, y) \]
  with Poiseuille law and Carter leak-off:
  \[ q = \frac{w}{\mu} \nabla p_f, \quad g_L = \frac{C_H}{\sqrt{t - t_0(x, y)}} - \frac{1}{\sqrt{t - t_0(x, y)}} \]

Tip Asymptotics

It can be shown that the equations governing the near tip behaviour of the fracture are identical to the governing equations for the problem of a steadily propagating semi-infinite fluid driven fracture [Desroches et al 1994, Garagash & Detournay 2000, Garagash et al 2011]. In the near-tip region, these equations provide the exact relations between the fracture parameters such as width and pressure, and the distance from the front.

For example, in the limiting toughness (Eq. a) and viscosity (Eq. b) dominated cases, the fracture width in the tip region is given by

\[ \psi = \frac{K_C}{E^3/2} \quad (a) \]

\[ \psi = 18\sqrt{3} \frac{\mu^3}{E^3/2} \quad (b) \]  

[Garagash et al 2000]

The complete solution capturing the transition between different propagation regimes has been obtained numerically [Garagash et al JFM 2011]. Here, we are using the approximation provided by Dontsov and Peirce [2015]. The ILSA scheme couples these tip solutions with the finite fracture discretization to resolve the tip behaviour at the sub-grid scale.

Validation

The scheme has been validated with a number of test cases. The figures below show the comparison of the solution computed by the ILSA scheme against the analytical solution for the case of viscosity dominated propagation.

Further test cases

- Confined propagation
- Asymmetric Stress contrast

References